The CMS High Granularity Calorimeter for the High Luminosity LHC

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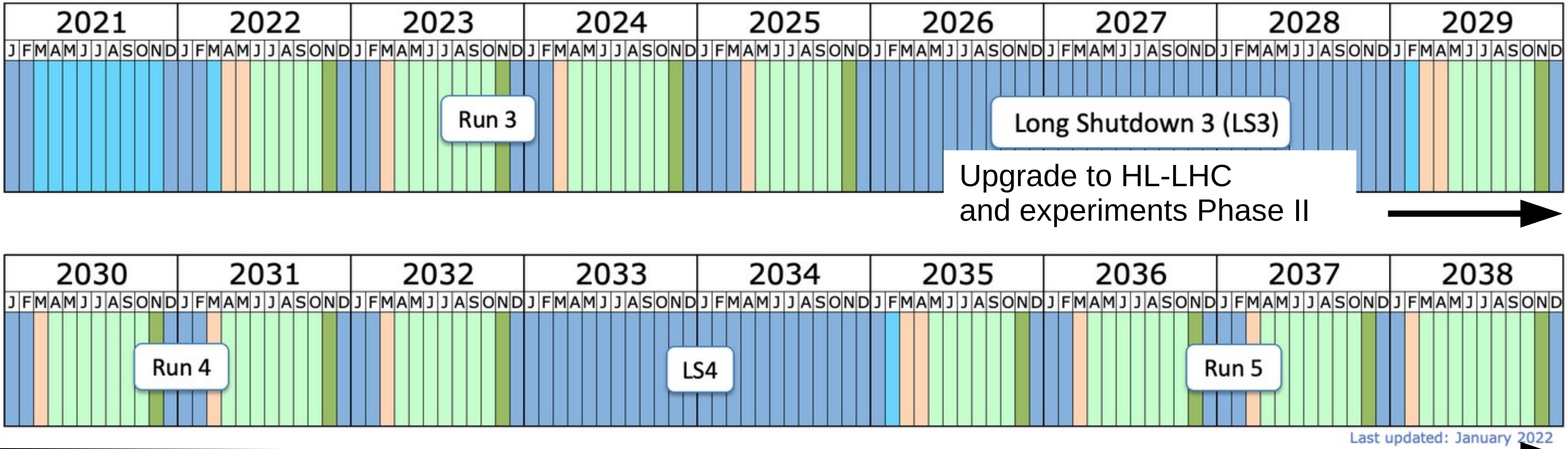
On behalf of the CMS collaboration

HEPHY, Vienna
23 Feb 2022

Outline

- Introduction: The HGCAL at the HL-LHC
- Scintillation detectors
- Silicon sensors and modules
- Electronics
- Novel reconstruction methods
- Summary

Upgrade to the High-Luminosity LHC



Integrated luminosity
$3000 fb^{-1}$

HL-LHC

Luminosity:	**$2 \times 10^{34}\ s^{-1}\ cm^{-2}$**	→	**$5 – 7.5 \times 10^{34}\ s^{-1}\ cm^{-2}$**
Pile-up events:	**O(40)**	→	**O(140-200)**

More radiation, more pile-up, higher density of tracks, more data...
The CMS detector will be upgraded to cope with the new challenges

Phase II Upgrade of CMS

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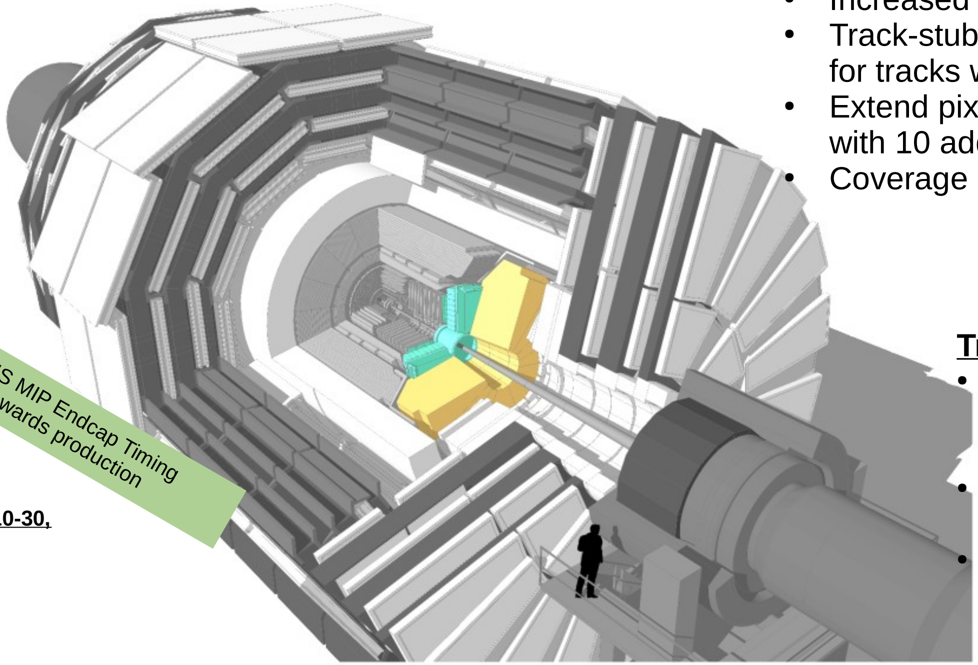
Calorimetry
- **Replacement of the calorimeter endcaps with HGCAL** ← **This talk!**
- New BE/FE electronics, HCAL partially new scintillator

G. Mazza, CMS ECAL upgrade for precision timing and energy measurements

Muon Systems
- New electronics
- Additional GEM and RPC chambers in 1.5 < η < 2.4
- Additional GEM station behind endcap calorimeter to increase muon coverage up to η < 3

K. Damanakis, The CMS Outer Tracker
D. Zuolo, Planar and 3D Silicon pixel sensors

Tracker
- Increased granularity
- Track-stub information to L1 trigger for tracks with pT >= 2GeV
- Extend pixel coverage up η = 4 with 10 additional pixel disks
- Coverage up to η = 3.8 (η = 4)



D. Spitzbart, The CMS MIP Endcap Timing Layer: From concept towards production

Timing Layer
- MIP timing to 30-60ps
- Coverage to η = 3

Trigger (L1 and HLT)
- Increase L1 trigger latency from 3.4µs to 12.5µs, upgrade of detector readout electronics
- L1 trigger rate: 500kHz (max 750kHz)
- HLT: 7.5kHz

DAQ and Trigger Control
- **Increase computing capacities by roughly factor of 10-30, rate of recorded data will increase to max. 7.5kHz**

Beam radiation instrumentation and luminosity
- New sensors, fully integrated into LHC control system

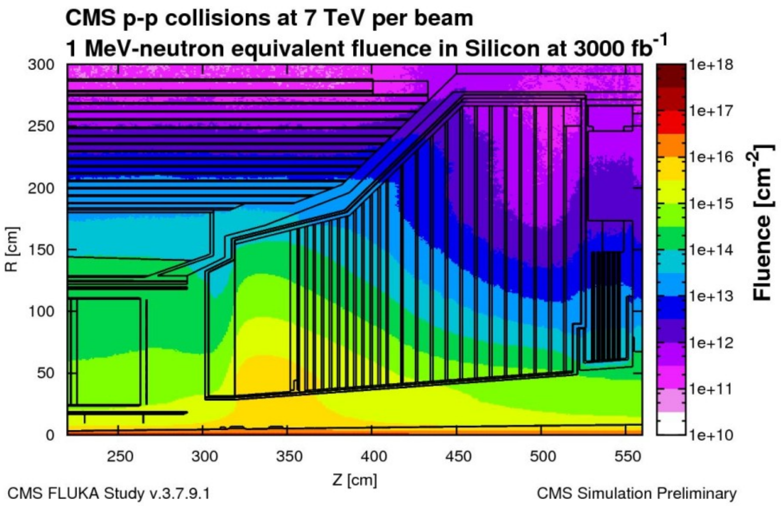
Software and Computing
- Improve algorithms, data storage etc. by factor of 4-12

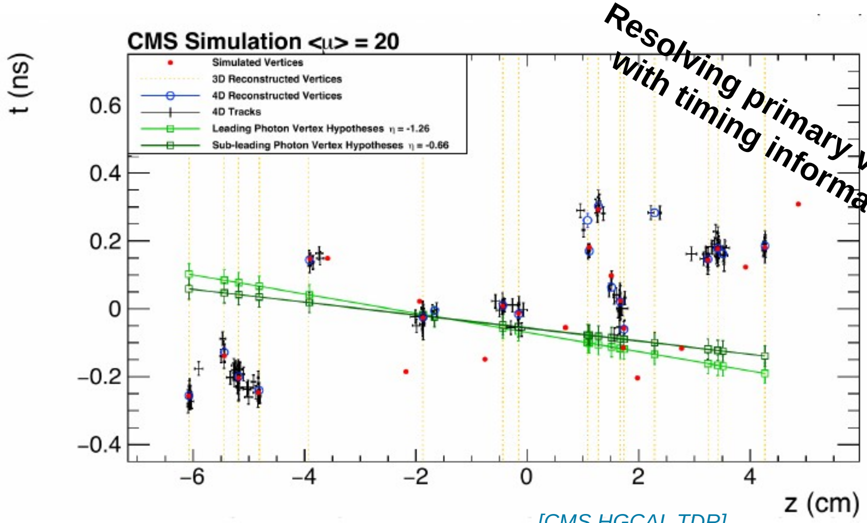
Challenging environment for calorimeter endcaps

Radiation background $10^{14}\ n_{eq}/cm^{-2}$ → $1 - 1.5 \times 10^{16}\ n_{eq}cm^{-2}$

The current CMS calorimeter endcaps will reach their end of life at the end of run 3.

- Increased radiation tolerance of sensors and electronics
- Precise timing measurements and increased granularity

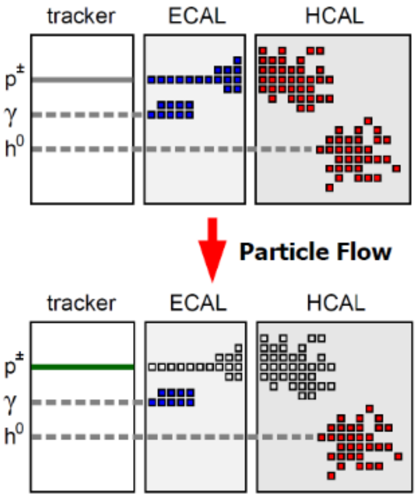




Resolving primary vertices with timing information

[CMS HGCAL TDR]
[CMS MTD TDR]

Particle Flow Reconstruction



Yong Liu, IAS Program on High Energy Physics (2022)

PF algorithms have been used already in the past (ALEPH, CDF, H1, ZEUS, ...)

Goal: Distinguish $Z \rightarrow$ jet+jet from $W \rightarrow$ jet+jet
Required energy resolution is about 3-4%

Can be achieved with **particle flow algorithms**

- For each particle within a jet: **Use the subdetector with optimal resolution**

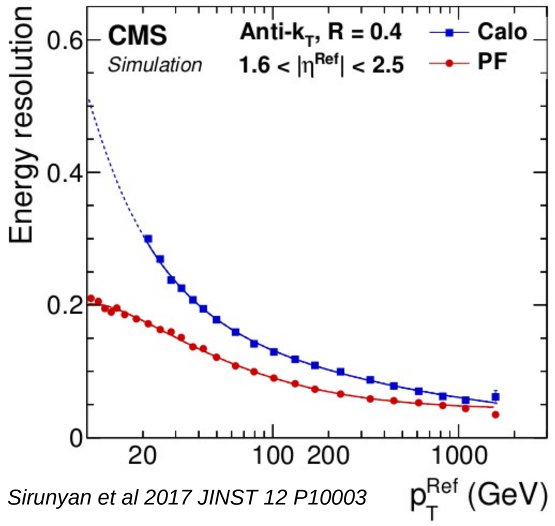
Typical jet:

~ 62% charged particles	Tracking
~ 27% photons	EM calorimeter
~ 10% neutral hadrons	HAD calorimeter
~~ 1% neutrinos~~	

Requires a compact, highly-granular calorimeter.

Compare e.g.:
- Current EM-Calo. endcap $PbWO_4$ crystals 8.2cm² front-face
- HGCAL EM silicon pad size 0.5 – 1.1cm²

Jet energy resolution in the endcap region



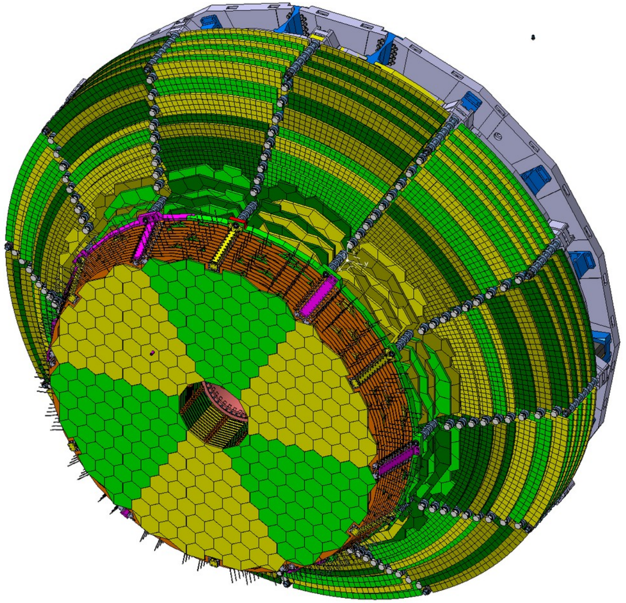
A.M. Sirunyan et al 2017 JINST 12 P10003

K. Krüger, Highly Granular Calorimeters for PF, TIPP21
K. Krüger, Particle Flow Calorimeters, EDIT2020

[CERN Courier, Particle flow in CMS]

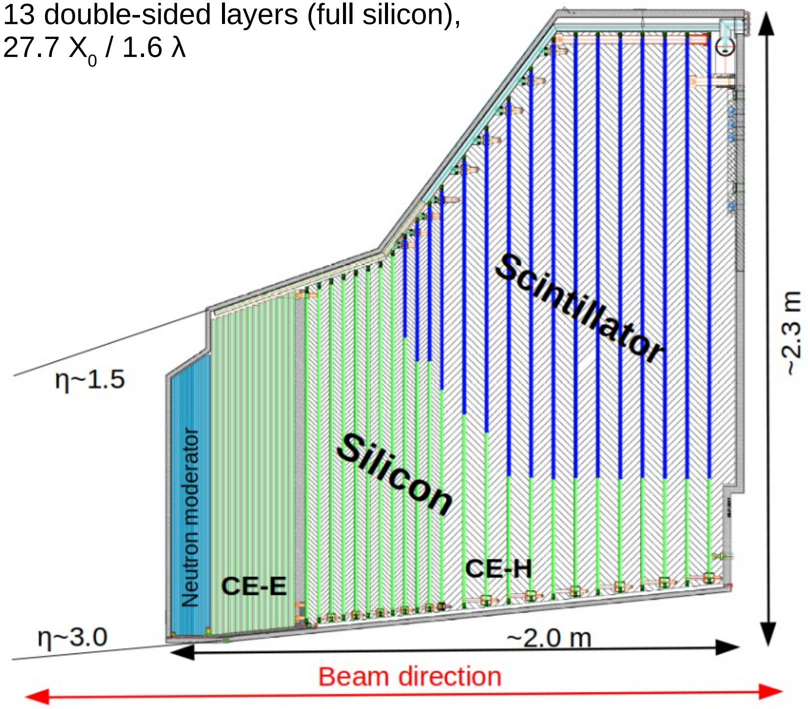
Layout of the HGCAL

Calorimeter endcaps:
- Coverage 1.5< | η | <3.0
- radiation tolerant
- high granularity
- precise hit/cluster timing
- Enhanced capability for particle flow reconstruction
- Operation at -30°C



Philippe Bloch, On-detector integration, 2022

CE-E (Electro-magnetic)
Active: Silicon
Passive: Cu, CuW, Pb absorbers
13 double-sided layers (full silicon),
27.7 X_0 / 1.6 λ



CE-H (Hadronic)
Active: Silicon + Scintillator / Silicon-photomultiplier
Passive: Steel absorbers
7 all-Si layers
21 layers, 9.4 λ (total)

Values for both endcaps:

Silicon
- 620m² of silicon
- 6M channels
- 30k modules
- 0.5 – 1.1cm² per cell

Scintillator + SiPM
- 400m² of scintillator
- 240k tiles + SiPM
- 4000 boards
- 4 - 30cm² per tile

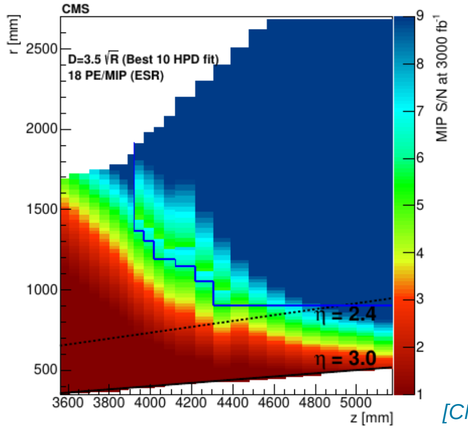
HGCAL design inspired by CALICE studies, e.g. C Adloff et al 2013 JINST 8 P09001

Scintillator + SiPM modules

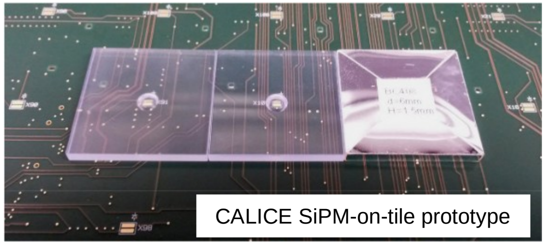
Scintillator tiles with SiPM readout used in low radiation regions (η>2.4)

- Require good MIP Signal/Noise after 3000fb^{-1}
- Tile size depends on radial-position (4cm² to 32cm²)
- Signal strength depends on tile and SiPM geometry → smaller tiles at lower radii

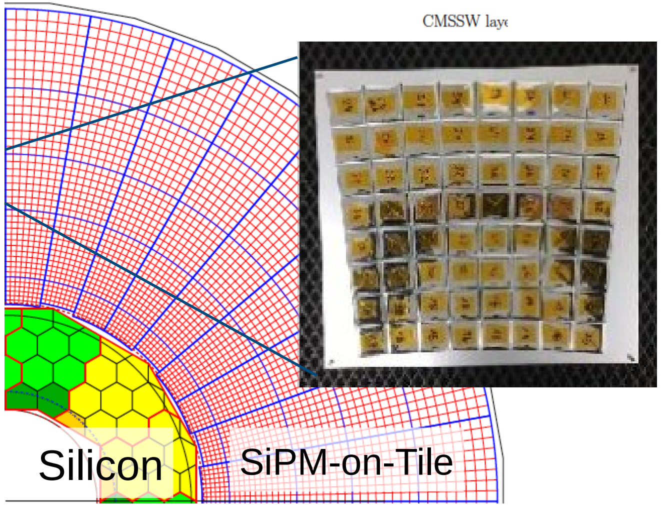
Projected signal-to-noise ratio after 3000fb^{-1}

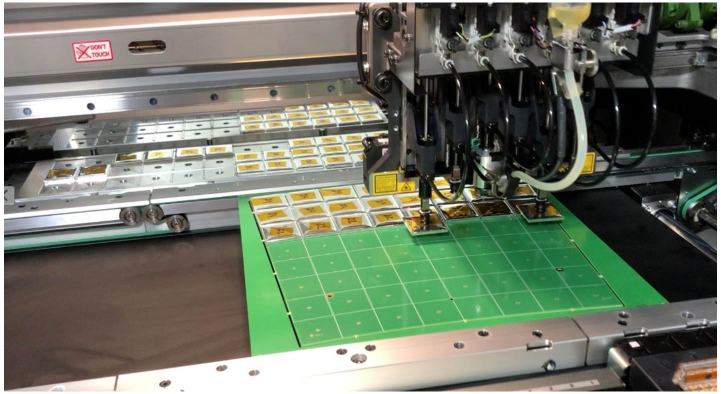


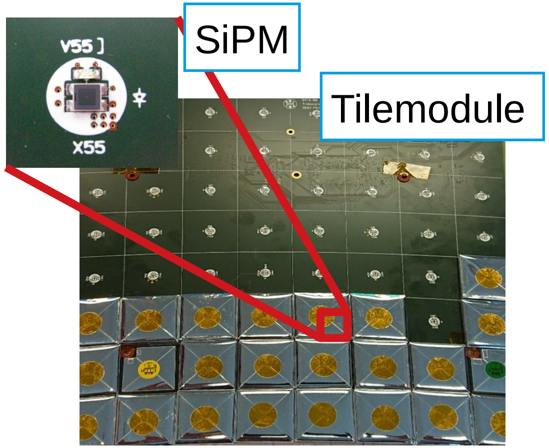
[CMS HGCAL TDR]



CALICE SiPM-on-tile prototype





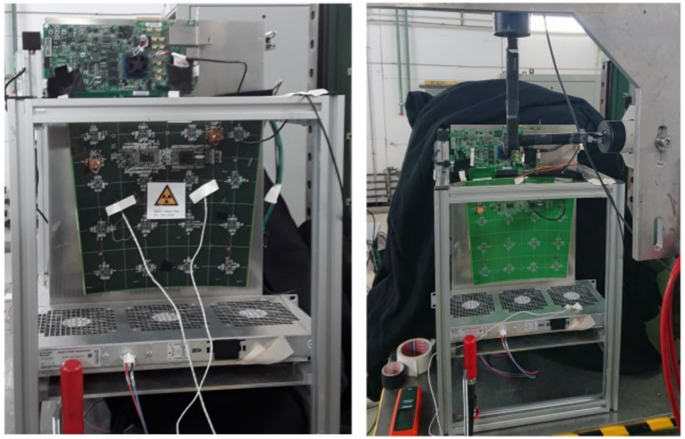


Scintillator + SiPM
Validation at DESY test-beams

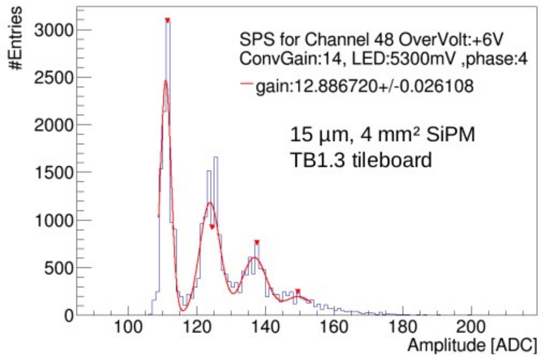
Two tileboards used at test-beams 2020/2021

- Performance estimates under realistic conditions with close to final read-out
- Realistic (mass-produced) tiles / automatic production and assembly procedures established

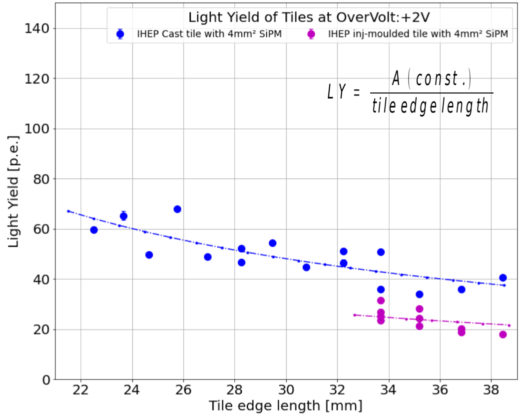
Pre-series in 2022, pre-production in 2023

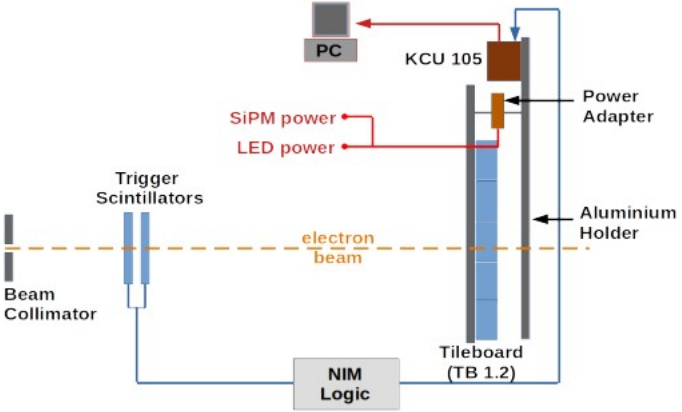


Single-photon-spectrum (LED)



Light yield with MIPs

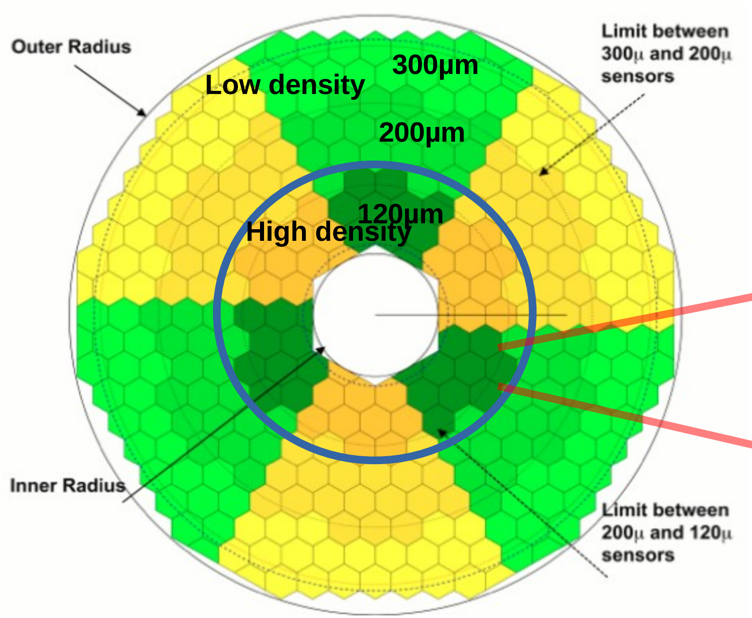




Malinda de Silva, Measurement of Light Yields - Based on Test Beam data between 2020-21

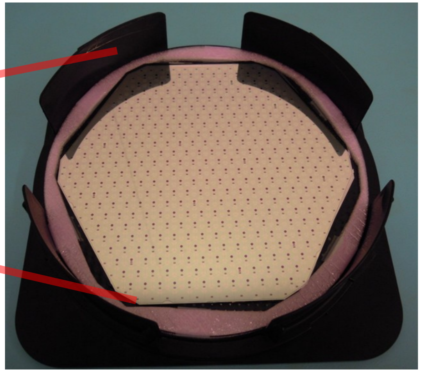
Silicon Sensors

Close to the beam axis:
- Higher radiation fluence
  → use of **thin** detectors
- Higher track density
  → **higher density** of sensor pads

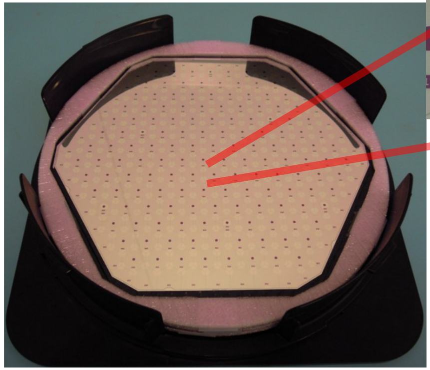


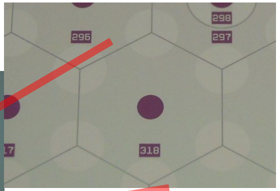
9th layer of CE-E

- Used in high occupancy / high radiation regions (full CE-E/ inner CE-H)
- Production on 8" wafer to reduce the number of modules
  - New production process!
- Hexagonal sensor shape
  - Maximize sensor area on wafer
  - Minimize overlap with full coverage, 'partial'-sensors to cover border regions
- Planar, DC-coupled, p-type sensors, no central biasing
- Produced by HPK



8" High-Density sensor
432 cells with ~0.5cm² size
120µm active thickness



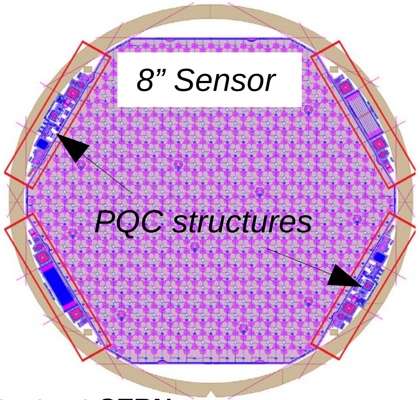


8" Low-Density sensor
192 cells with ~1.1cm² size
300µm and 200µm active thickness

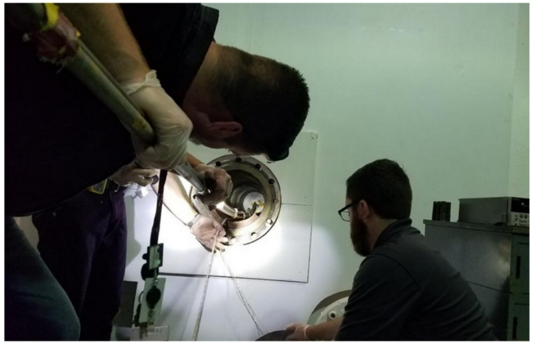
Silicon Sensors

- Prototyping with pre-series full size 8” V2 sensor,
- Extensive electrical / irradiation tests ongoing
- Irradiation of full size sensors at the
- Rhode Island Nuclear Science Center, RINSC (Brown University)
- First full modules are being built

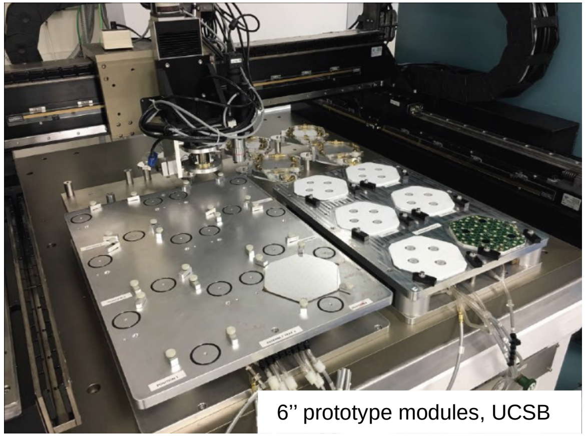
Pre-series in 2022, pre-production in 2023



8” irradiation slot at RINSC

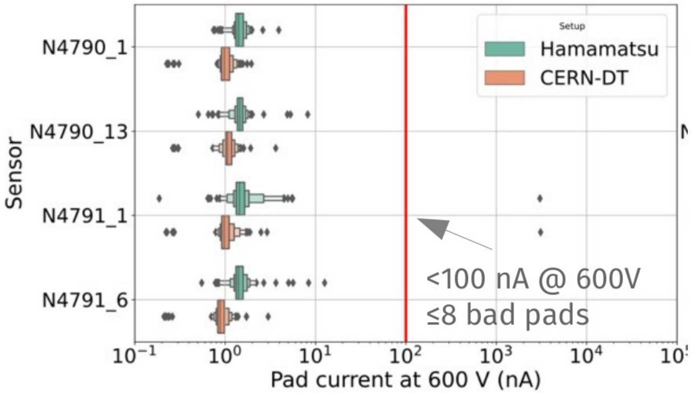


Automatic module assembly

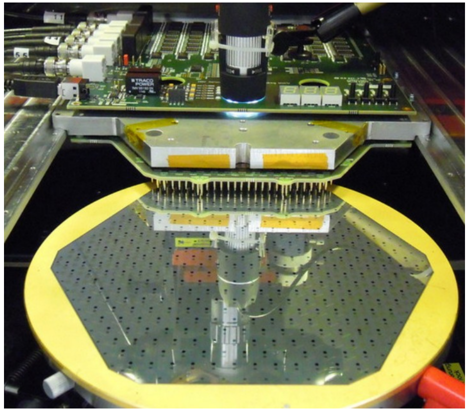


6’’ prototype modules, UCSB

Electrical tests at CERN



Probe-card for electrical tests



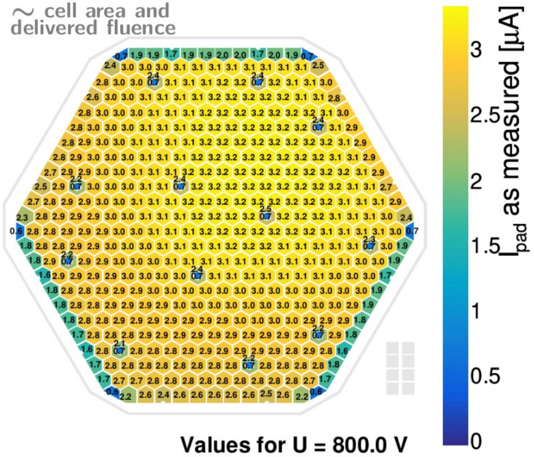
Silicon Sensors: Radiation hardness

Neutron irradiation of 8”-sensors to $10^{16} n_{eq}/cm^2$ at RINSC, US

Irradiated + tested different production splits / different sensor geometries
- ✔ Identified best production process
- ✔ Proven radiation hardness of silicon sensors

Leakage current

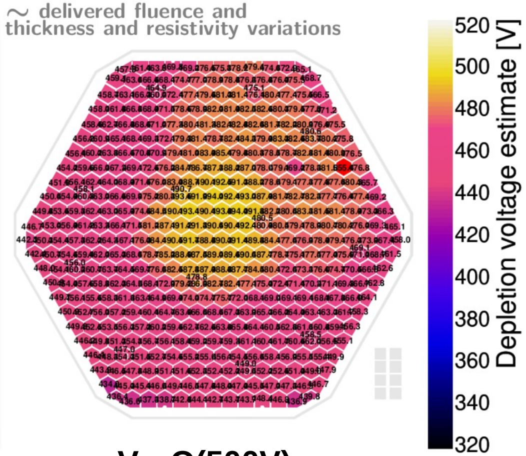
~ cell area and delivered fluence



I_{pad} O(3μA)

Depletion voltage

~ delivered fluence and thickness and resistivity variations



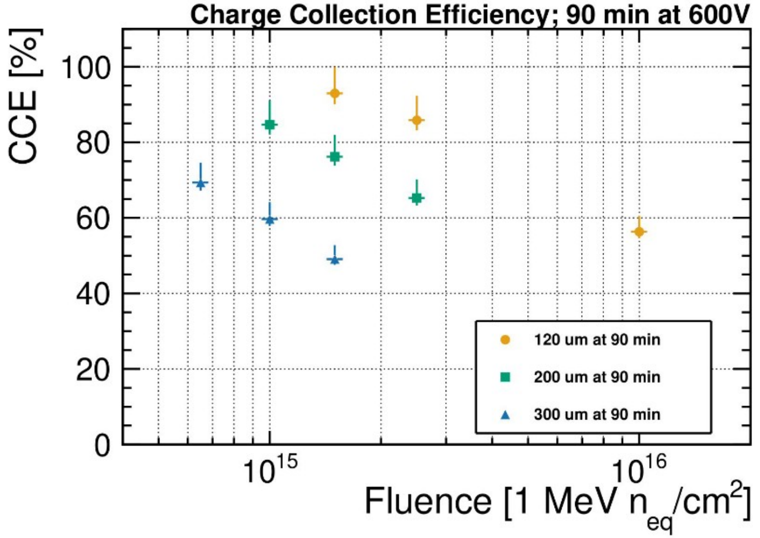
V_{fd} O(500V)

Full sensor irradiation: 120μm, $10^{16} n_{eq}/cm^2$

Thickness	Lower fluence	Higher fluence
300 μm	1×10^{14}	5×10^{14}
200 μm	5×10^{14}	2.5×10^{15}
120 μm	2.0×10^{15}	7×10^{15}

Reduction in collected charge with fluence studied and found to be in line with TDR expectations.

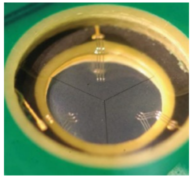
Qualification of radiation hardness of V1 prototype sensors



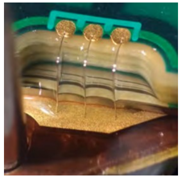
Pedro Almeida, IR laser TCT diode CCE results

Silicon Modules

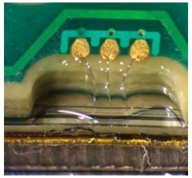
Sensor cell contact



Bias voltage



Guard ring contact

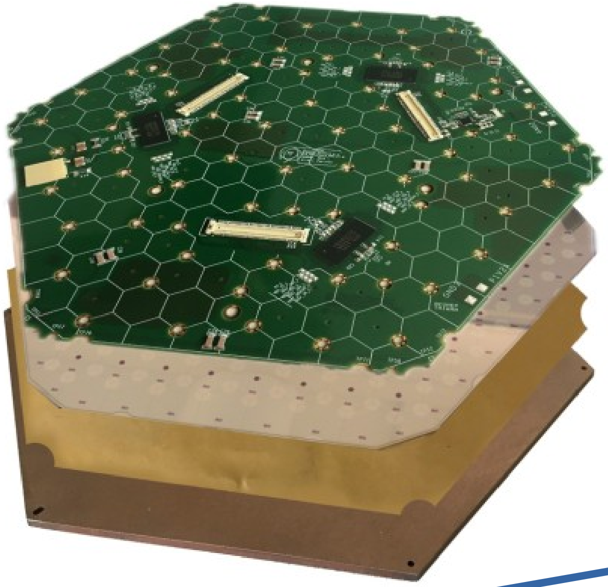


Hexaboard

Sensor

Kapton sheet

Cu/W base plate

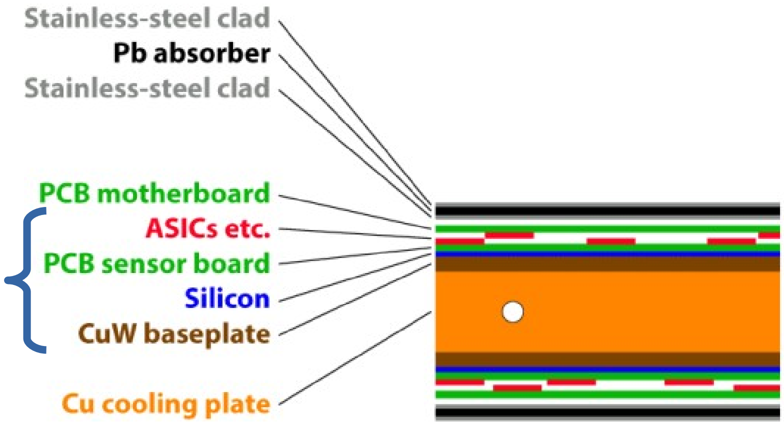


Sensor-PCB (‘Hexaboard’)
- Read-out (HGCROC) of sensor cells + bias supply
- Connects to motherboard for data transfer

Silicon sensor

Kapton sheet
- Isolation to baseplate + bias supply to sensor back side

Baseplate
- Rigidity, contributes to absorber material



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Module Integration

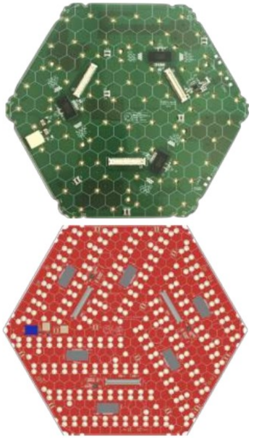
HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

CE-E:
- Double-sided cassettes, self supporting, integrated absorber (Cu cooling plate, Pb cover)

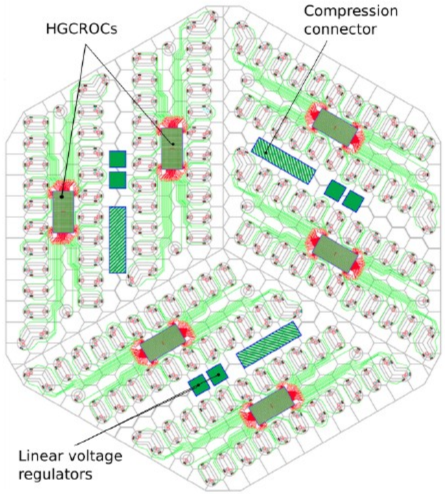
CE-H:
- Single-sided cassettes, mounted between steel absorbers
- All-Si and mixed cassettes (Si modules, SiPM-on-tile modules)

- **Module** is composed of the Si sensor and hexaboard PCB
- Passive **wagon board** is connected to one to three modules
- **Engine board** is connected to two wagon boards
- Data transmission via optical links to off-detector electronics

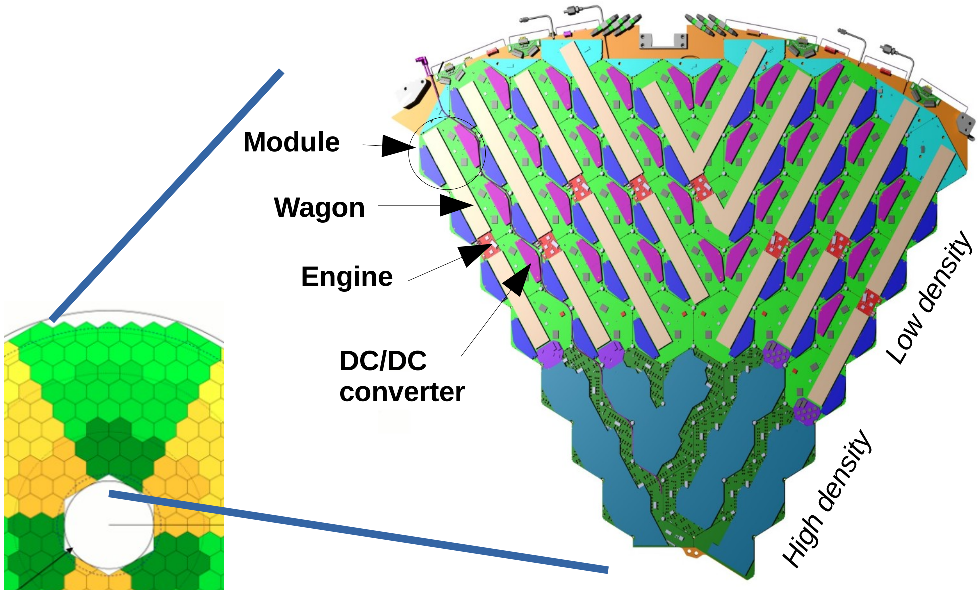
Low density 3x HGCROC



High density 6x HGCROC



Hexaboard PCB

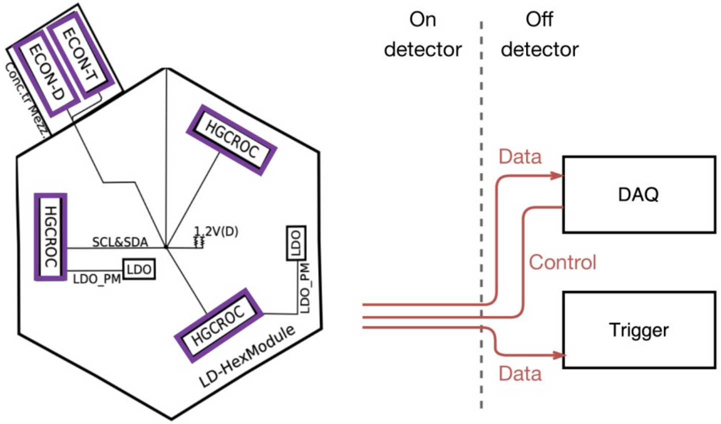


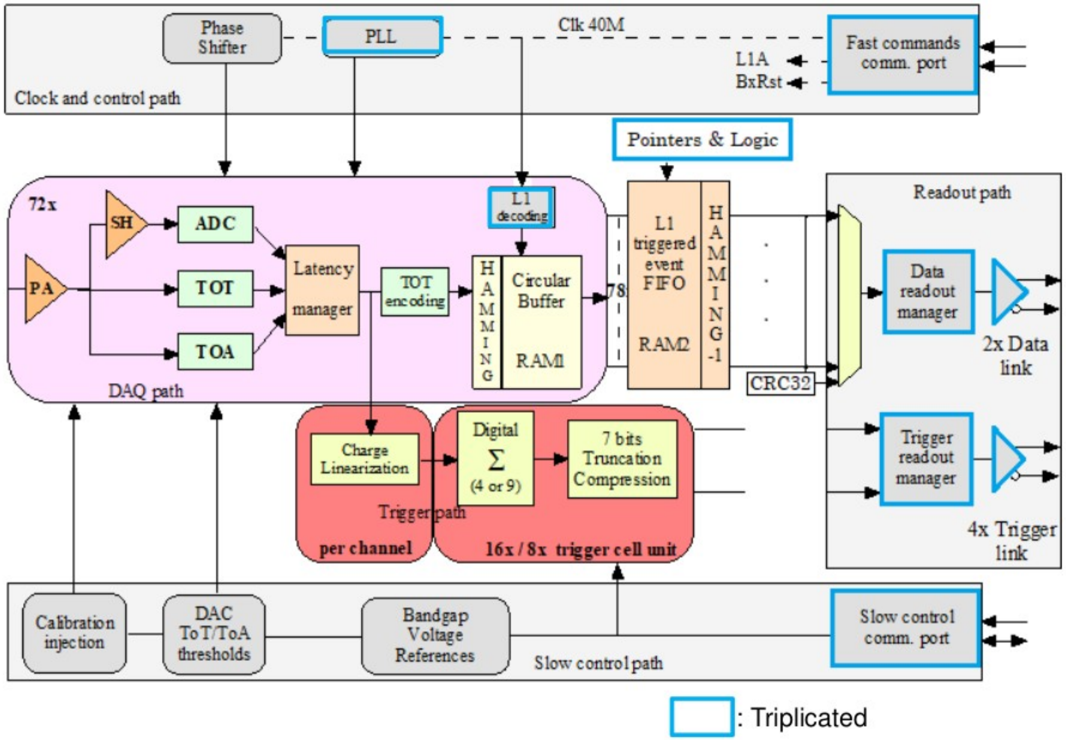
All-silicon cassette

Electronics: HGCROC

Requirements for read-out electronics

- **Three chips in one:**
  - **ADC + TOT: High dynamic range (0.2fC – 10pC)**
  - **TOA: Timing information O(30ps)**
- Scintillator ROC adds current conveyor to silicon ROC
- Low noise (< 2500e⁻)
- Radiation tolerant
- < 20mW per channel





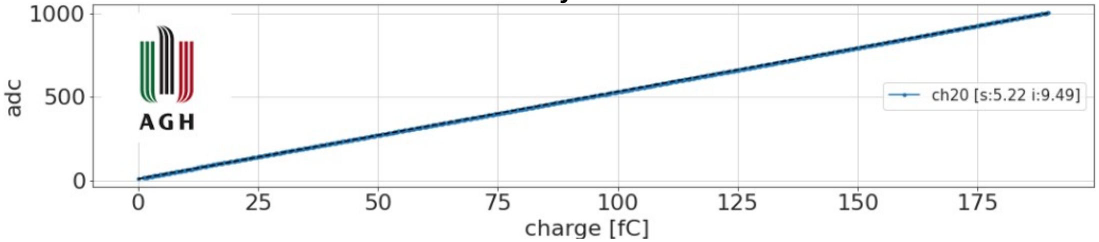
ECON-T: Aggregation and compression of cell sums for L1 trigger
ECON-D: Common-mode estimation and zero-suppression of triggered data

2020 S. Extier_HGCROC-Si_and_HGCROC-SiPM_the_front-end_readout_ASICs_for_the_CMS_HGCAL
A. Lobanov 2018 JINST 13 C02056

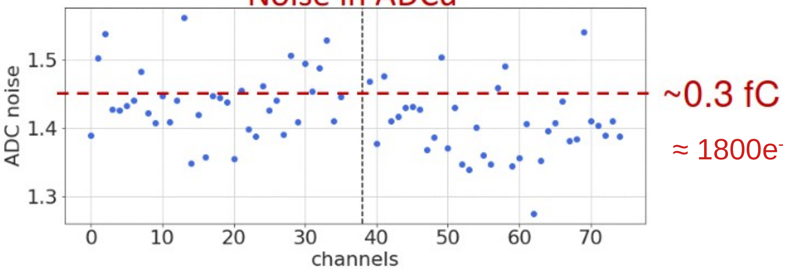
HGCAL Read-out

HGCROC V3

ADC linearity within +/- 0.5%



Similarly promising results for TOT, up to 10pC

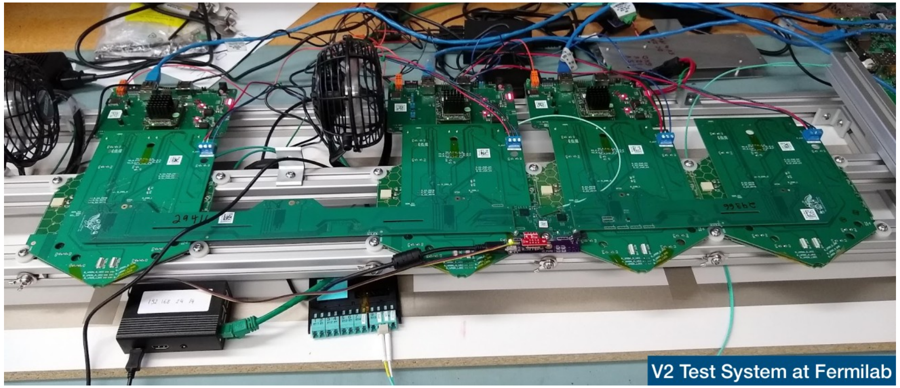


HGCROC3 integrates all the functionalities + a fully radiation tolerant digital part
– Charge linearity within 1%
– TOA and TOT jitter less than 13 ps and 25 ps respectively

Frederic Dulucq, TWEPP21

Good progress on HGCAL read-out system tests
- Produced prototypes or emulators for all main components
- Full chain of data capture and front-end configuration

Scintillator V3 system assembly in the coming months at UMN, CERN and DESY

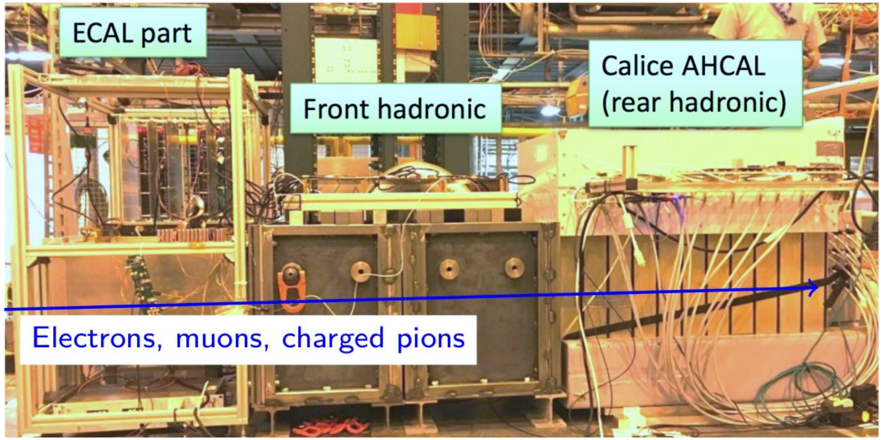


Silicon V2 system test at Fermilab (similar setup at CERN)
- Engine with 2 wagons and 4 hexaboards

N. Strobbe, TWEPP21

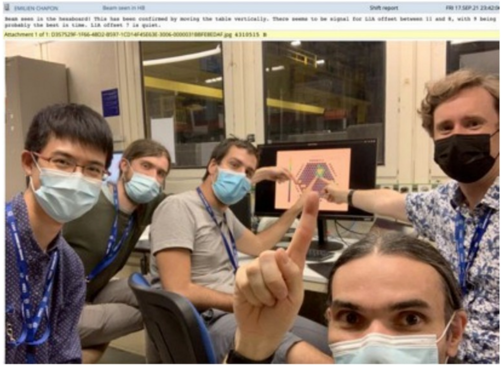
Beam-tests

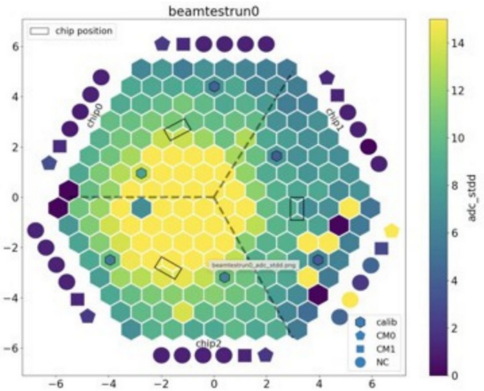
Beam tests in 2016–2018
using 6-inch silicon modules and CALICE Scint. AHCAL



E. Sicking, PSD21

Test beam at H2 beamline at CERN (SPS) Sept/Oct 2021





IHEP LD Module with HGCROCv2, 300mm silicon in September 21 beam test

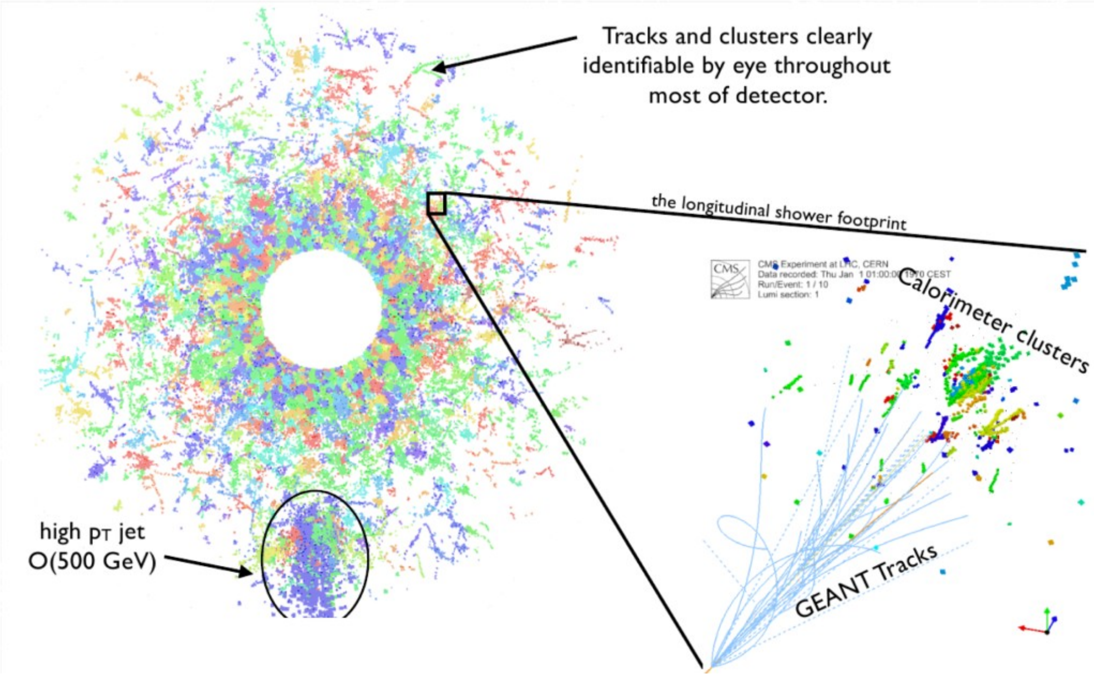
- Noise / MIP response in realistic environment in Si modules
- ROCv2 (Sep), ROCv3 (Oct), explored a range of working parameters with e^- -beams

- **Analysis on-going**

P. Ferreira da Silva CMS week, Dec. 21

Novel Reconstruction Methods

- The construction of a high granularity calorimeter is a unique opportunity to employ modern computing technologies
- **Heterogeneous computing:** GPUs can be used
- **Machine learning:** Use of Convolutional Neural Networks (CNN) e.g. for particle ID

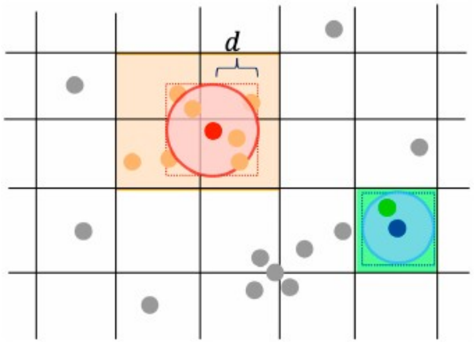


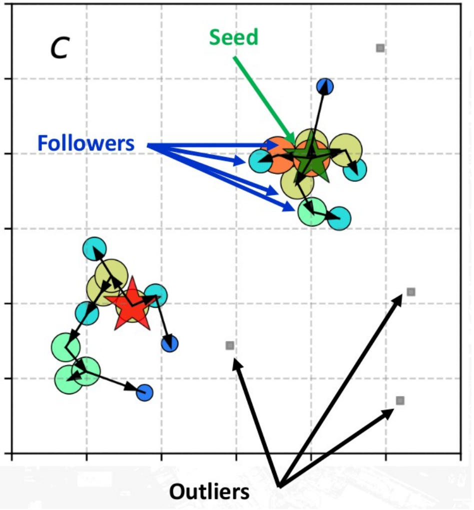
CLUE: Clustering of energy

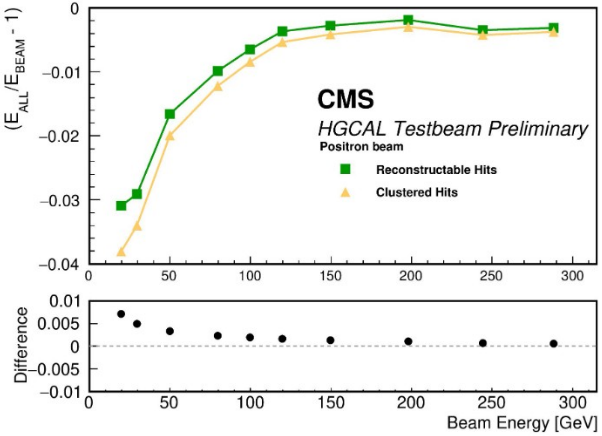
- Large number of recorded hits (~ 10^5 per event)
  - Reduce the number of objects by building clusters of energy
- Can be parallelized and runs on GPUs

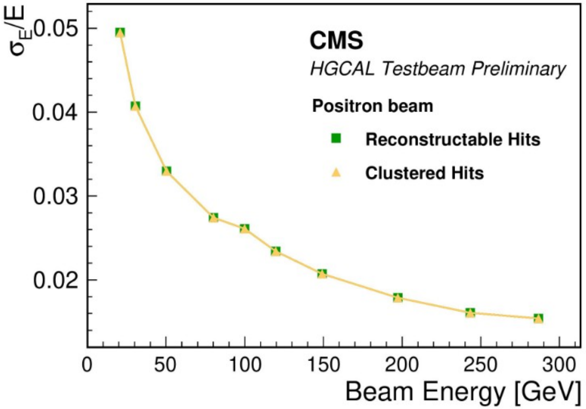
CLUE algorithm:

- Calculate energy density in a distance d
- Calculate 'nearest-higher' hit
- Define seeds and outliers







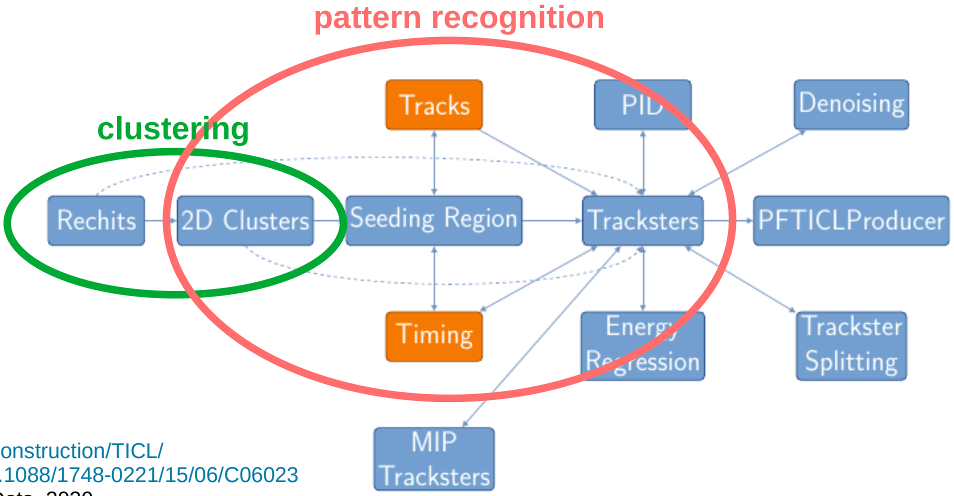


M. Rovere, https://doi.org/10.3389/fdata.2020.591315
L. Gouskos, Connecting the dots 2020

TICL: The Iterative Clustering

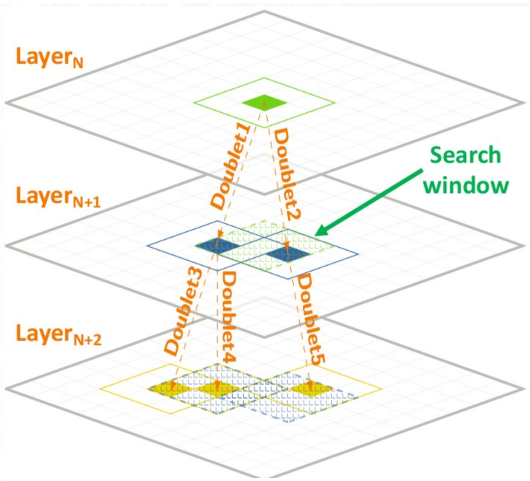
- Particles deposit energy and create ‘Rechits’;
- Rechits are clustered together to form 2D LayerClusters (CLUE algorithm)
- Clusters on different layers are linked together to form Tracksters (particle showers)

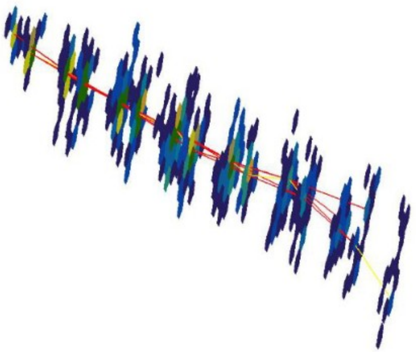
Iterative approach:
- Reconstruct simpler objects first
- Mask reconstructed objects
- Reconstruct more complex objects in following iterations



https://hgcal.web.cern.ch/Reconstruction/TICL/
A. Di Pilato, https://doi.org/10.1088/1748-0221/15/06/C06023
L. Gouskos, Connecting the Dots, 2020

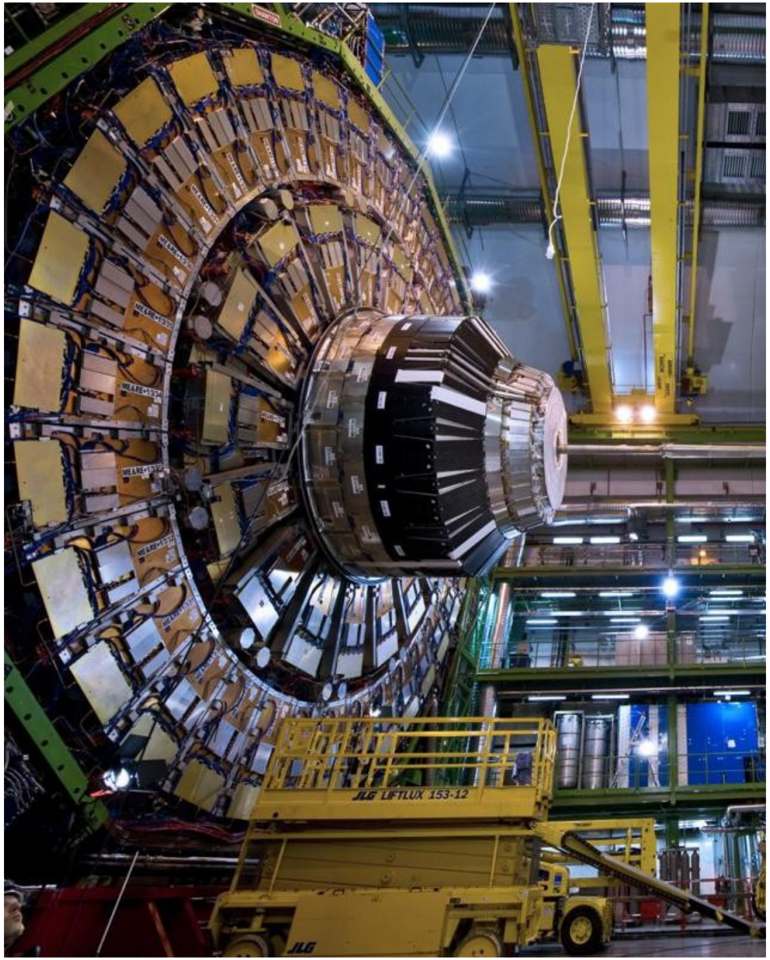
Forming doublets from 2D clusters





Trackster connecting several 2D Layer Clusters

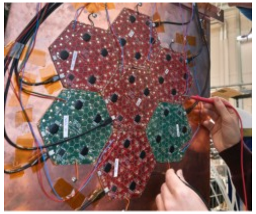
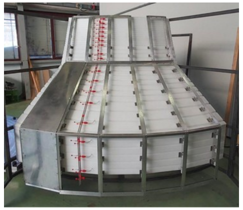
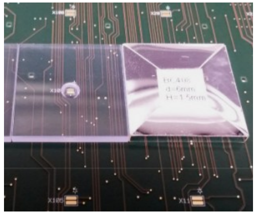
Summary

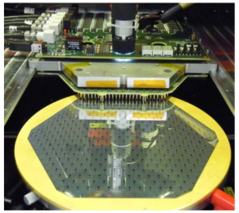


CMS is constructing a High Granularity Calorimeter for the HL-LHC

- $620m^2$ of silicon and $400m^2$ of scintillator
- 6M read out channel
- High precision spatial / energy / timing information

- Silicon sensors / SiPM-on-Tile in pre-series, preparing for production, starting 2022
- Electronics systems well advanced, components in close-to-final version being tested, full system tests ongoing
- Validation of prototypes in test-beams successful

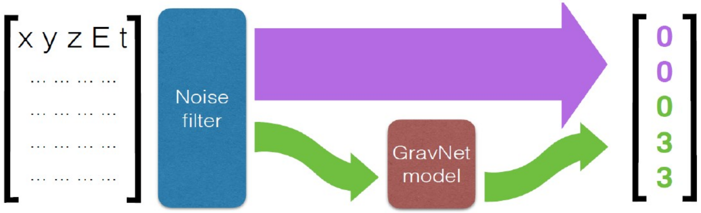


Backup

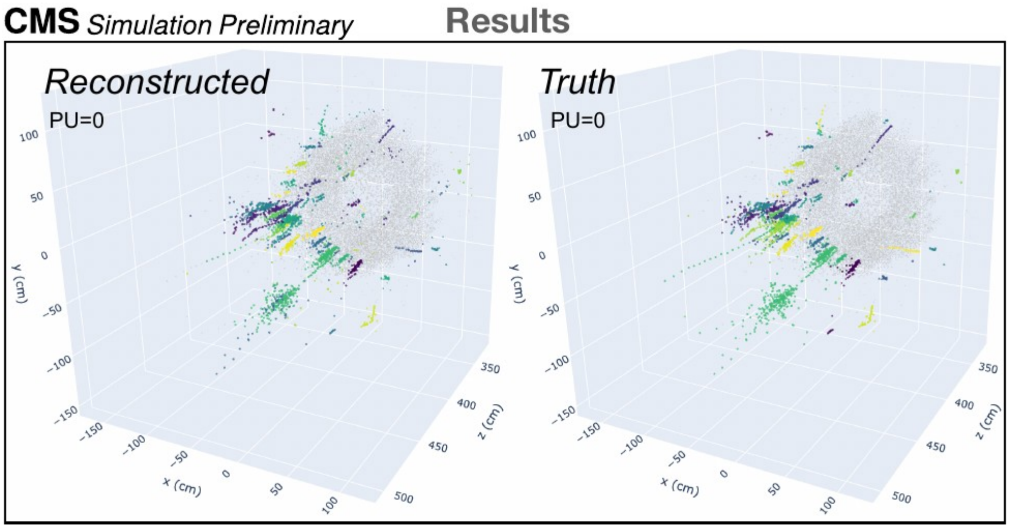
Graph Neural Networks for Reconstruction

Developing a one-pass, completely Machine Learning based reconstruction
Algorithm identifies clusters of hits from the same particle

[1902.07987]
[2002.03605]



T. Klijnsma, GNN-based end-to-end reconstruction in the CMS Phase 2 High-Granularity Calorimeter



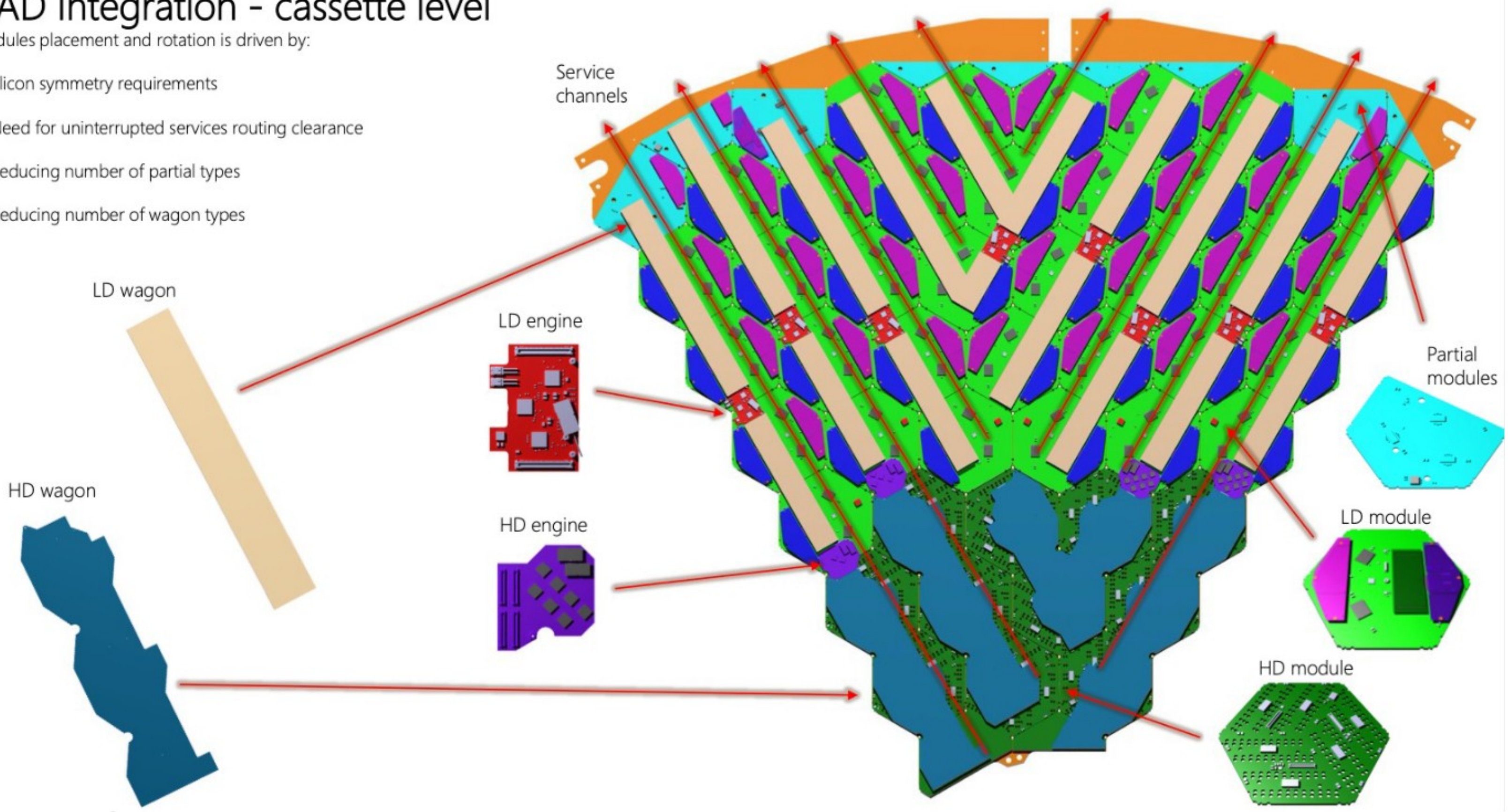
Simulated tau leptons in 0-PU, including shower development due to particle-detector interaction

Silicon Cassette

CAD Integration - cassette level

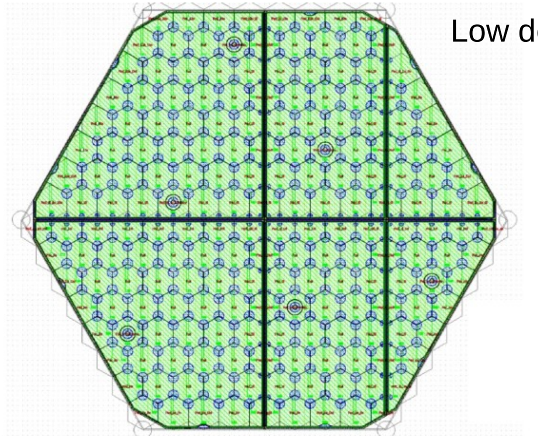
Modules placement and rotation is driven by:

1) Silicon symmetry requirements
2) Need for uninterrupted services routing clearance
3) Reducing number of partial types
4) Reducing number of wagon types

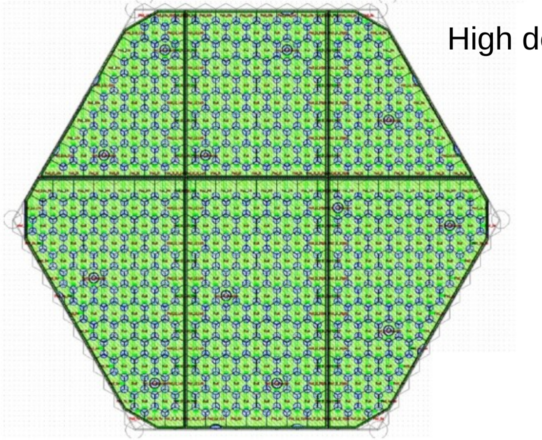


P. Aspell, CMS Upgrade meeting Jan. 22

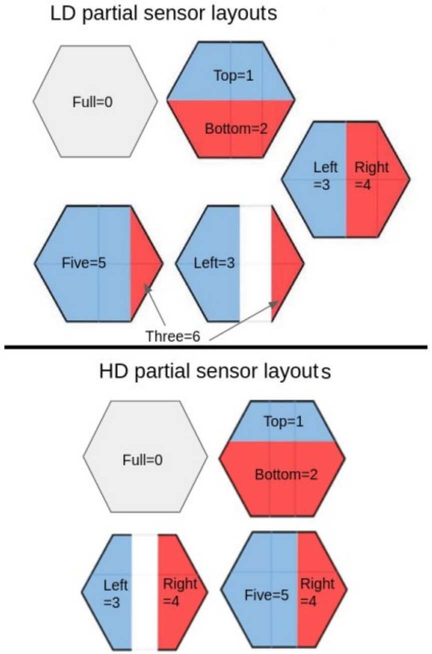
Partial silicon sensors



Low density geometry



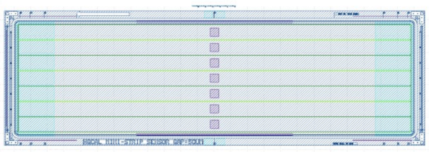
High density geometry



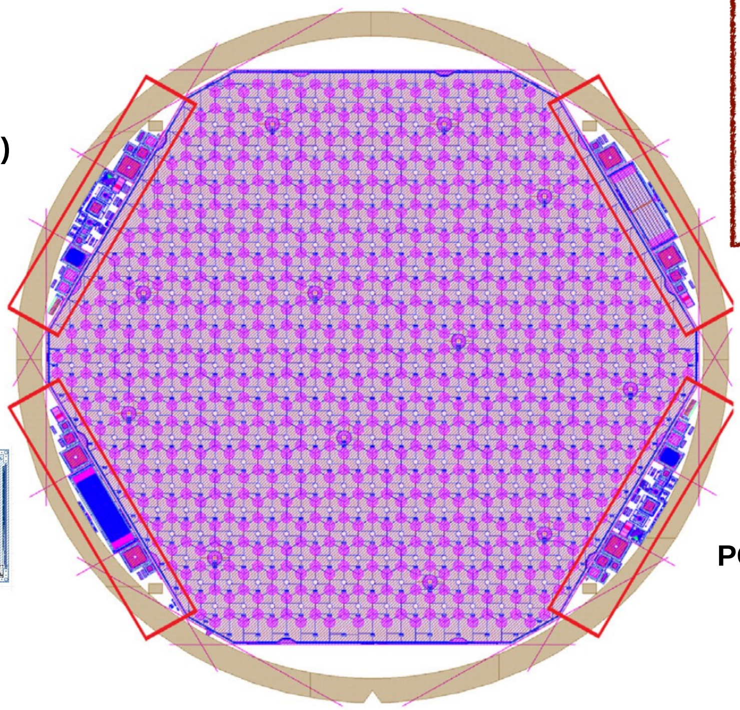
Border regions are covered with partial sensors

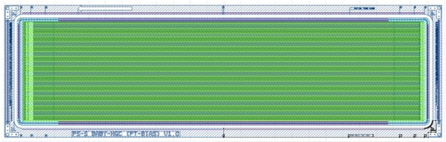
- Increased coverage
- Increased complexity

Test Structures on HGC wafer



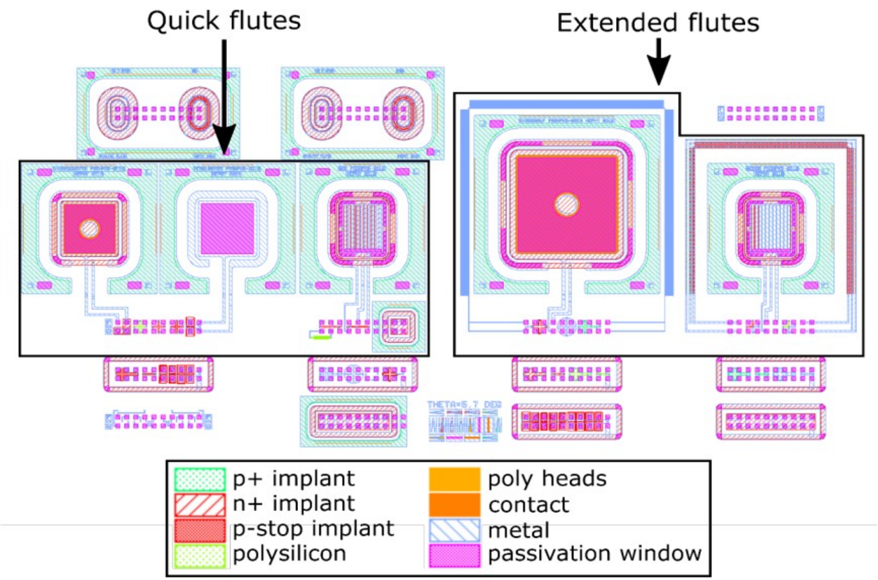
HGC-like Ministrip Sensor
- 7 DC coupled strip
- Direct bias
- 0.95 mm pitch
- 23.541 mm length
- Resembles HGC sensor





Tracker-like Microstrip Sensor
- 60 AC coupled strips
- Punch through bias
- 0.1 mm pitch
- 23.526 mm length
- Resembles tracker sensor (though no poly silicon bias)

PQC structures



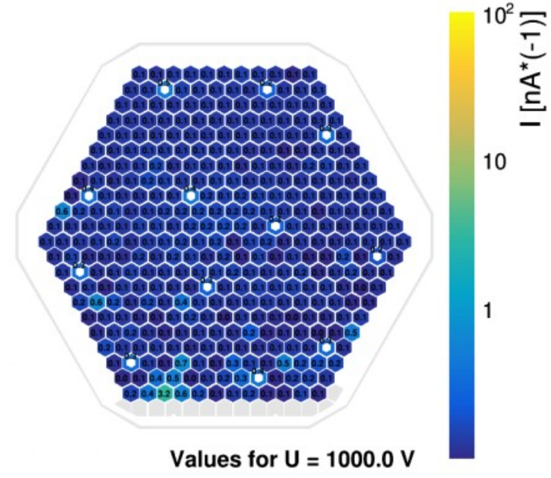
PQC measurements for development:
- Establish differences between production processes
- Evaluate impact of design parameters on sensor performance
- Correlate PQC measurements with sensor tests after irradiation

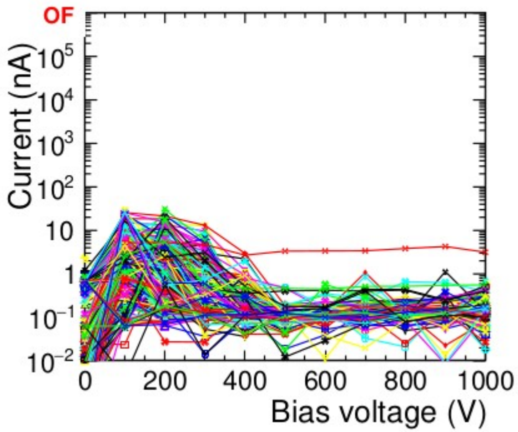
PQC measurements during production:
- Continuously monitor design parameters to identify irregularities / changes in the production process
- Prevent bad sensors from being used for the experiment

Different structures to asses design parameters
- Diode: Current and Capacitance characteristics, Full-depletion voltage
- Gate-Controlled-Diode (GCD): Surface current, surface generation velocity, Si-SiO2 interface quality, interface traps
- Field-Effect-Transistor (FET): Threshold voltage is sensitive to p-stop doping and interstrip resistance
- Metal-Oxide-Semiconductor (MOS) Capacitor: Oxide thickness and quality (amount of fixed oxide charges)
- Van-der-Pauw structures: Sheet resistance of various materials / implants

Automatic IV+CV analysis workflow

Eva Sicking, P2UG, May 2021





- Compare HPK 7-needle IV results to technical specifications from tender
- Automatically grade sensor as "passed" or "failed"
- Can be run on CMS full-wafer probe card data and HPK 7-needle data
- In use at CERN and FSU, developed at CERN

- Sensor has been graded with checksCollectionID 2.
- Global characteristics:
  - Current at 600V I600 (normalised to 20 deg Celsius): <= 100 μA integrated over the sensor and guard rings: Passed
  - I800 < 2.5 x I600: Passed
  - Allowed number of bad pads <= 8 for full-sized sensors: Passed
  - Allowed number of adjacent bad pads <= 2: Passed
- Per-pad characteristics used to define bad pads if any of the following are not met:
  - Current at 600V I600 (normalised to 20 deg Celsius): <= 100 nA/pad: **0** pads not fulfilling, namely **[]**
  - I800 < 2.5 x I600: **0** pads not fulfilling, namely **[]**

Sensor has PASSED the requirements.

Silicon sensor quality criteria

- Requirements described in frame contract ▸ Reference: IT-4508/EP/CMS
- **HPK qualification tests** before sensor delivery
  - 1.a **Per-cell current**
    - $I_{p,600\,V}$: $\leq$ 100 nA, per pad p,
    - $I_{p,800\,V}$ $<$ 2.5 $\cdot$ $I_{p,600\,V}$, per pad p
    - At most 8 bad pads per sensor, at most 2 adjacent bad pads
  - 1.b **Total current**
    - $I_{tot,\,600\,V}$: $\leq$ 100 µA, including guard ring
    - $I_{tot,\,800\,V}$ $<$ 2.5 $\cdot$ $I_{tot,\,600\,V}$
  - 1.c **Capacitance and depletion voltage** for one diode
- **CMS qualification tests**
  1. Validate HPK results and track changes
  2. Capacitance and depletion voltage across full sensor
  3. Inter-pad capacitance and resistance
  4. Development of sensor characteristics after irradiation and annealing, including noise and charge collection efficiency
  5. Sensor properties from dedicated test structures (e.g. V_{fb})

European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

Group Code: EP/CMS
The CMS HGCAL Upgrade Project IT-4508/EP/CMS

Invitation to Tender

Technical Specification
for the Supply of Silicon Sensors for the CMS HGCAL upgrade project

Abstract

The upgrades to the ATLAS and CMS experiments, in view of the HL-LHC program, require the supply of silicon sensors on a much larger scale than for previous projects in High Energy Physics. Following the Market Survey MS-4086/EP, this is one of a series of three Invitations to Tender for the supply of silicon sensors, one each for the ATLAS ITk Strips, CMS Outer Tracker and CMS HGCAL upgrade projects respectively.

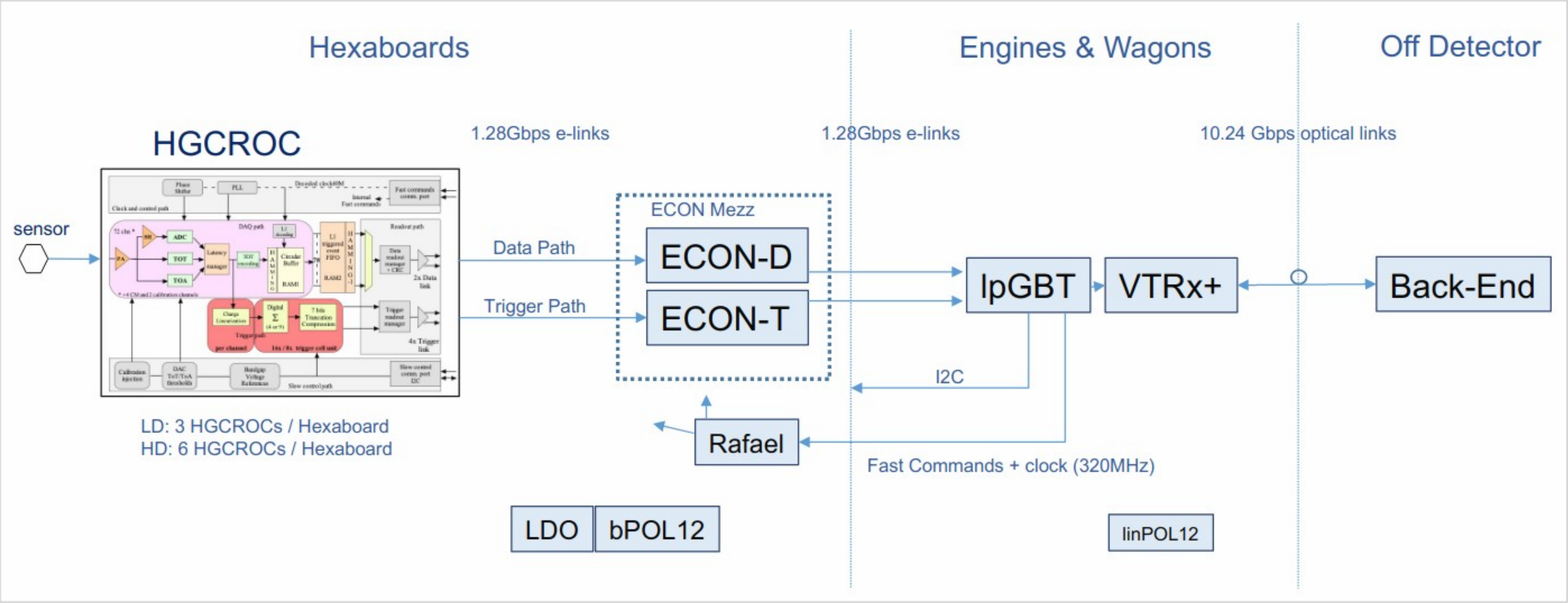
This technical specification concerns the supply of silicon sensors for the CMS HGCAL.

The provisions of this Technical Specification shall prevail on the General Conditions of CERN Contracts (CERN/FC/6211-II). The General Conditions of CERN Contracts shall apply insofar as they are neither countermanded nor expressly modified in this Technical Specification.

April 2019

E. Sicking, P2UG

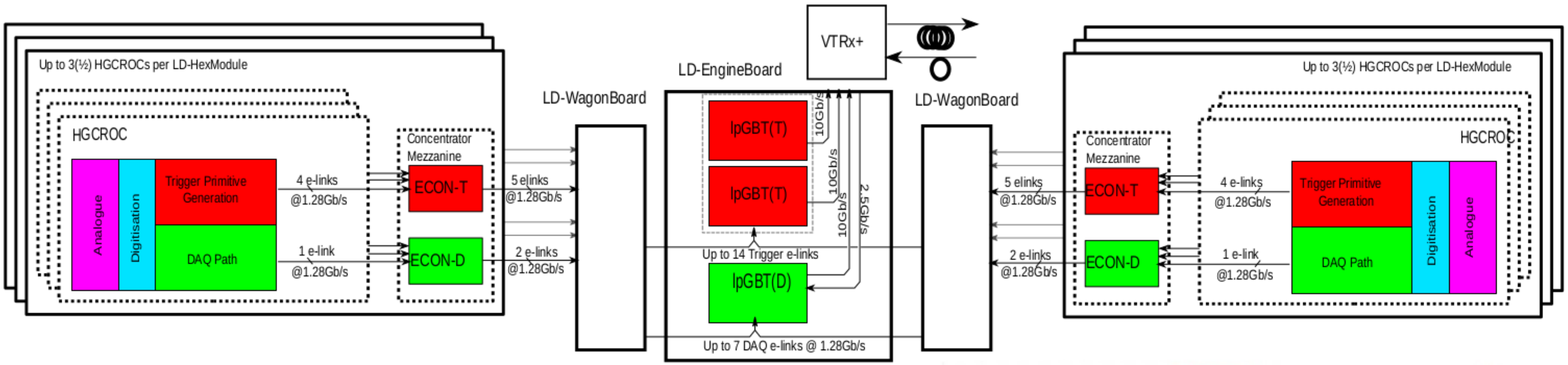
HGCAL Electronics

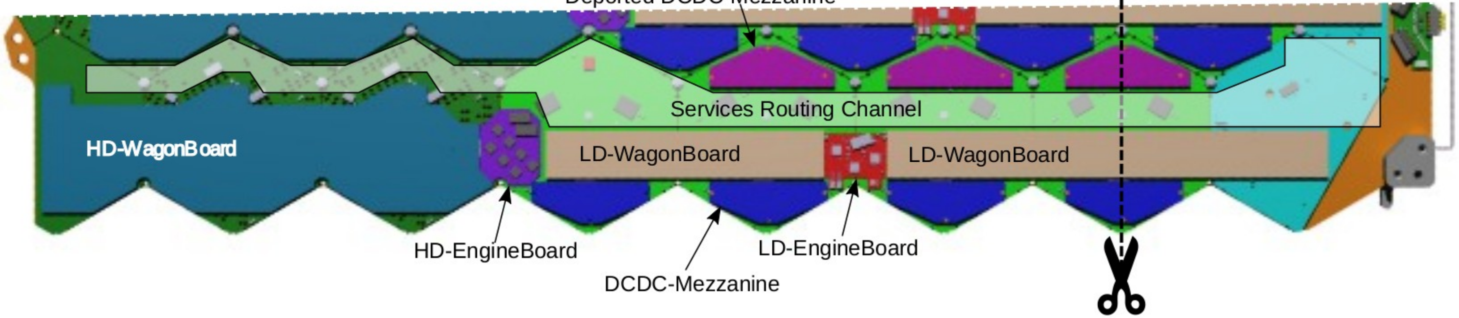


HGCROC: HGC Read out chip
ECON: elink concentrator (Data / Trigger)

P. Aspell, CMS Upgrade meeting Jan. 22

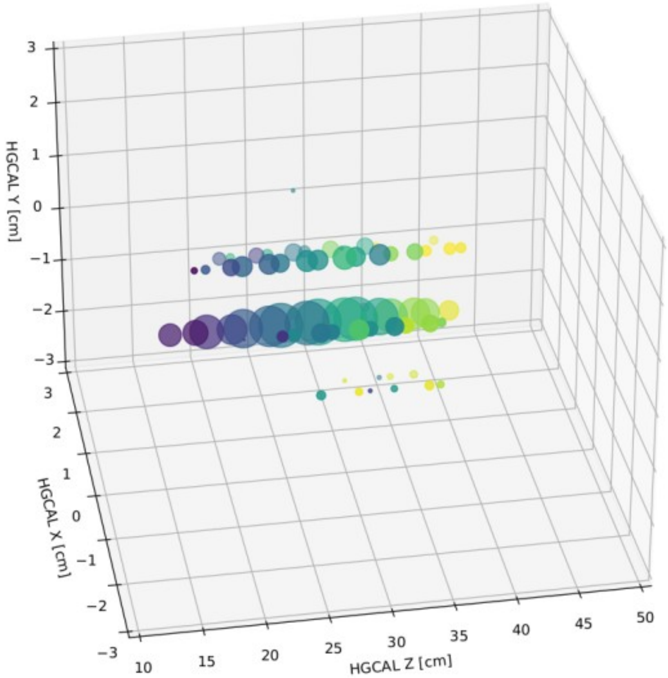
Engines and Wagons





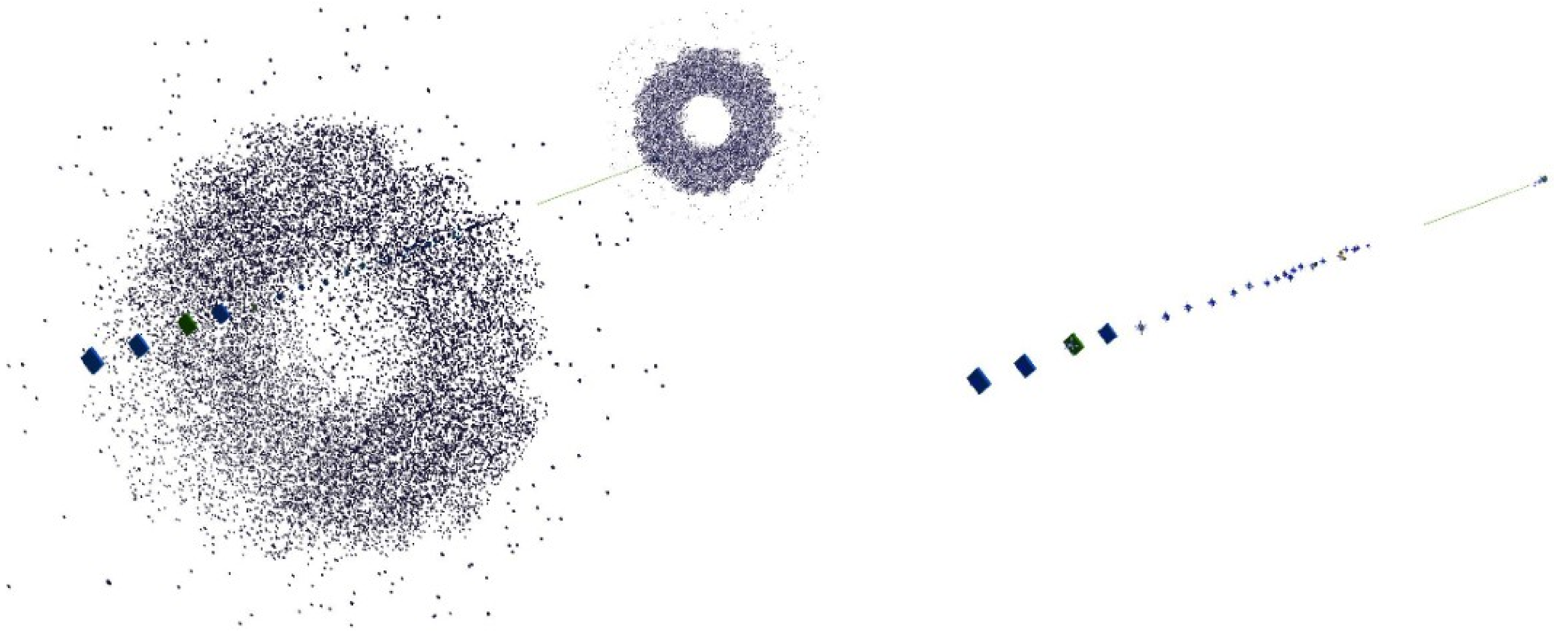
ECAL shower time resolved

Snapshot of shower development within ∼1 ns (blue=early, yellow=late)



Eva Sicking, PSD21

CLUE: Noise suppression



Caption. Event displays of an event of single muon generated with transverse momentum of 10 GeV without pileup. On the left the RecHits view, with electronic noise enabled. On the right, the same event after applying the CLUE layer clustering algorithm.